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SCIENTIFIC PAPER

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EFFECTS OF MICROWAVE PRETREATMENT ON THE ENERGY AND EXERGY UTILIZATION IN THIN-LAYER DRYING OF SOUR POMEGRANATE ARILS

Energy and exergy analyses may be considered as important tools for design, analysis and optimization of thermal systems. This paper reports on energy and exergy analyses of thin-layer drying of sour pomegranate arils with microwave pretreatment. There were two microwave pretreatments (100 W for 20 min and 200 W for 10 min) along with a control treatment (convection drying with no microwave pretreatment). Experiments were carried out at three air temperatures (50, 60 and 70 °C) and three air velocities (0.5, 1 and 1.5 m/s). Results showed that energy utilization and energy utilization ratio increased with time, while exergy efficiency decreased. Energy utilization and drying time decreased considerably with microwave pretreatment of pomegranate arils. The minimum values of exergy loss and exergy efficiency were associated with the 200 W microwave pretreatment, while they were maximum for control treatment.

Keywords: energy and exergy; microwave pretreatment; thin layer drying; pomegranate.

Drying is known as one of the best methods to preserve fruits like pomegranate. Water is removed by drying, preventing microorganism growth and harmful chemical reactions consequently leading to longer storage life [1]. Mathematical models of thin-layer drying provide little information on the dryer energy analysis, so they do not constitute complete tools for design and optimization purposes. Thermodynamic analysis, particularly exergy analysis, can play an important role in system design, analysis and thermal system optimization. Exergy analysis evaluates the accessible energy at several points and presents useful information for design methodology and part selection in a dryer [2-4]. Exergy refers to the maximum work produced by heat and vapor at the equilibrium state [5-6].

Akpinar [7] analyzed the effective and wasted energy in convection drying of pepper slices. Their experiments were conducted at three temperature levels of 55, 60 and 70 °C and air velocity of 1.5 m/s. The effective energy varied from 189.949 to 3732.961 kJ/s in the time period of 9600 to 18000 s (depending on drying air temperature). The required energy for drying potato slices, at temperature levels of 60, 70, and 80 °C, relative humidity of 10 to 20% and air velocity of 1 and 1.5 m/s was calculated by Akpinar [8]. Their tests lasted 10 to 12 h and energy loss was obtained to be 0 to 1.796 kJ/s [8]. Midilli and Kucuk [9] studied energy and exergy for solar drying of pistachio. Having used peeled and fresh samples of pistachio, they concluded that the moisture structure and moisture content were significant factors in increasing energy consumption and decreasing losses [9]. Energy and exergy analysis for drying red pepper slices in a laboratory dryer indicated that energy utilization and energy utilization ratio increased with temperature, while they decreased with time. Also, exergy loss increased with temperature whereas exergy efficiency did not show any specific trend [3]. Akpinar [10] applied the first and second law of thermodynamics for drying pumpkin in a rotary dryer with two trays. The results proved that energy consumption was much

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higher in the primary tray compared to the secondary one.

Energy and exergy for drying timber in a heat pump has also been studied. Experiments carried out at a single temperature and hot air velocity indicated that energy utilization and energy utilization ratio decreased with time, while exergy efficiency increased [11].

Corzo [4] studied energy and exergy for thin-layer drying of coroba slices in convection dryer. They conducted the experiments at three temperature levels of 71, 82 and 93 °C and three air velocity levels of 0.82, 1 and 1.18 m/s. The results demonstrated that air temperature and velocity increase (at two levels of 82 and 93 °C) significantly raised energy utilization; while changing air velocity at the temperature of 71 °C had no significant effect on energy utilization.

Although a considerable amount of data has been reported in the literature regarding the energy consumption of drying various agricultural like cherry fruits [12] carrot slices [13], vegetable [14], kaolin [15], mulberry [16], garlic cloves [17], longan [18], pomegranate arils [19], nettle leaves [20], berberis fruit [21], azarole [22], carrot slices [23], mulberry [24], porous media [25] okra [26] and yeast cells [27], little information is available on the effect of microwave pretreatment on energy and exergy utilization in drying of various agriculture products. The main objective of this research is comparison of microwave pretreatment and control treatment effects on energy and exergy utilization in the drying of pomegranate arils.

MATERIALS AND METHODS

Fresh samples of sour pomegranate were collected from Jooybar in Mazandaran province of Iran. Samples were stored at 5 °C in the refrigerator. Initial moisture content of pomegranate arils was found to be 73.1% (w.b.) using oven drying [28]. The experiments were carried out at three air temperature levels of 50, 60 and 70 °C and three levels of air velocity, namely 0.5, 1 and 1.5 m/s. Three treatments (hot air only) including control treatment, microwave pretreatment of 100 W power for 20 min, and microwave pretreatment of 200 W power for 10 min were also considered. The ambient air humidity was 0.037±0.004 kg/kg dry air.

Air parameters were adjusted by measuring temperature and velocity using a thermometer (Lutron, TM-925, Taiwan) and anemometer (Anemometer, Lutron-YK, 80AM, Taiwan). A pressure gauge (PVR 0606A81, Italy) was used to measure the air pressure and a moisture meter (Testo 650, 05366501, Germany) was applied to measure the air relative humidity (input and output). Moreover, the microwave pretreatment of pomegranate arils was implemented using a microwave oven (Samsung, 75DK300036V, model M945, Korea). The experimental set up is illustrated in Figure 1.

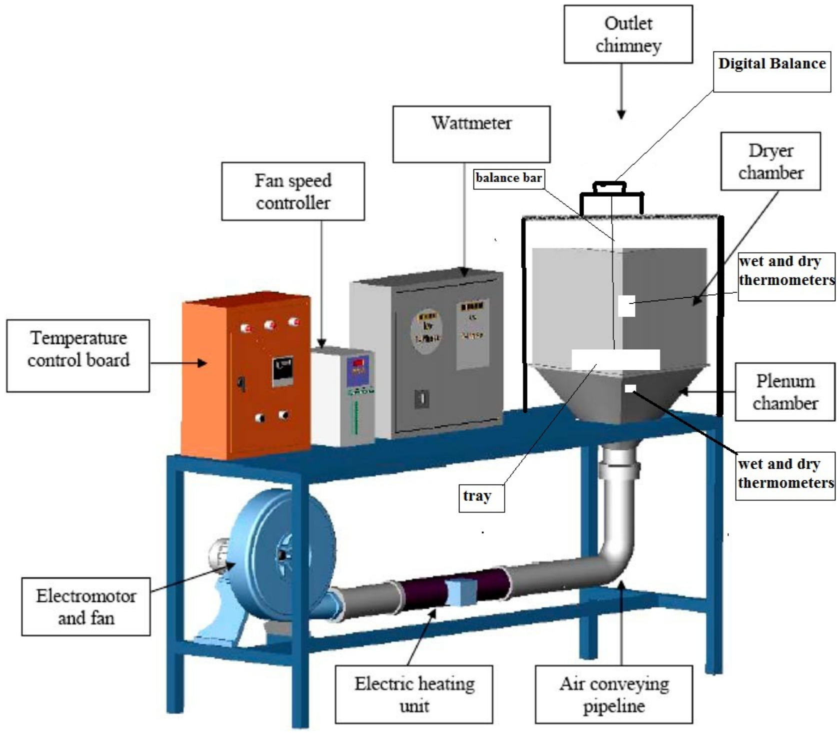


Figure 1. Experimental set-up.

Heater energy utilization can be calculated using the conservation energy law of thermodynamics [4]:

$$EU = m_{\mathrm{da}}(h_{\mathrm{dai}} - h_{\mathrm{dao}}) \tag{1}$$

Inlet and outlet air flow

All of the inlet air passes through the dryer section, thus the outlet air flow is equal to inlet flow due to mass conservation law:

$$m_{\mathrm{ai}} = m_{\mathrm{ao}} \tag{2}$$

Inlet and outlet air enthalpy

Values of the inlet and outlet air enthalpy are equal to the sum of dry air enthalpy and water vapor enthalpy. Eq. (3) is frequently used by researchers to determine air enthalpy [3-4]:

$$h_{\mathrm{da}} = C_{\mathrm{pda}}(T - T_{\infty}) + h_{\mathrm{fg}}w \tag{3}$$

Calculation of air specific heat

Air specific heat is calculated from Eq. (4). The constant 1.004 is the specific heat of dry air [2]:

$$C_{\mathrm{pda}} = 1.004 + 1.88w \tag{4}$$

Converting the relative humidity to moisture ratio

Relative humidity was converted to moisture ratio using Eq. (5) [2,4,10]:

$$w = 0.622\frac{\varphi P_{\mathrm{vs}}}{P - \varphi P_{\mathrm{vs}}} \tag{5}$$

Calculation of energy utilization ratio

The ratio of energy utilization to the provided energy in the dryer chamber is defined as energy utilization ratio, and is calculated using Eq. (6) [4]:

$$EUR = \frac{h_{\mathrm{dai}} - h_{\mathrm{dao}}}{h_{\mathrm{dai}} - h_{\mathrm{da}\infty}} \tag{6}$$

Exergy analysis

The sum of inlet and outlet air exergy for fresh and dried product is calculated using the second law of thermodynamics. The basic method for exergy analysis of dryer chamber is calculation at the stable conditions. For this purpose, Eq. (7) was used [3-4]:

$$Ex = \dot{m}_{\mathrm{da}}C_{\mathrm{pda}}\left[(T - T_{\infty}) - T_{\infty}\ln(\frac{T}{T_{\infty}})\right] \tag{7}$$

Exergy loss is determined by Eq. (8):

$$Ex_{\mathrm{loss}} = Ex_{\mathrm{inflow}} - Ex_{\mathrm{outflow}} \tag{8}$$

The exergy efficiency can be calculated using Eq. (9) [2]:

$$Ex_{\mathrm{eff}} = \frac{\sum Ex_i - \sum Ex_l}{\sum Ex_i} = \frac{\sum Ex_{\mathrm{o}}}{\sum Ex_i} \tag{9}$$

Ex_{eff} is 100% when no more moisture is extracted, and decreases as drying begins.

RESULTS AND DISCUSSION

Energy analysis

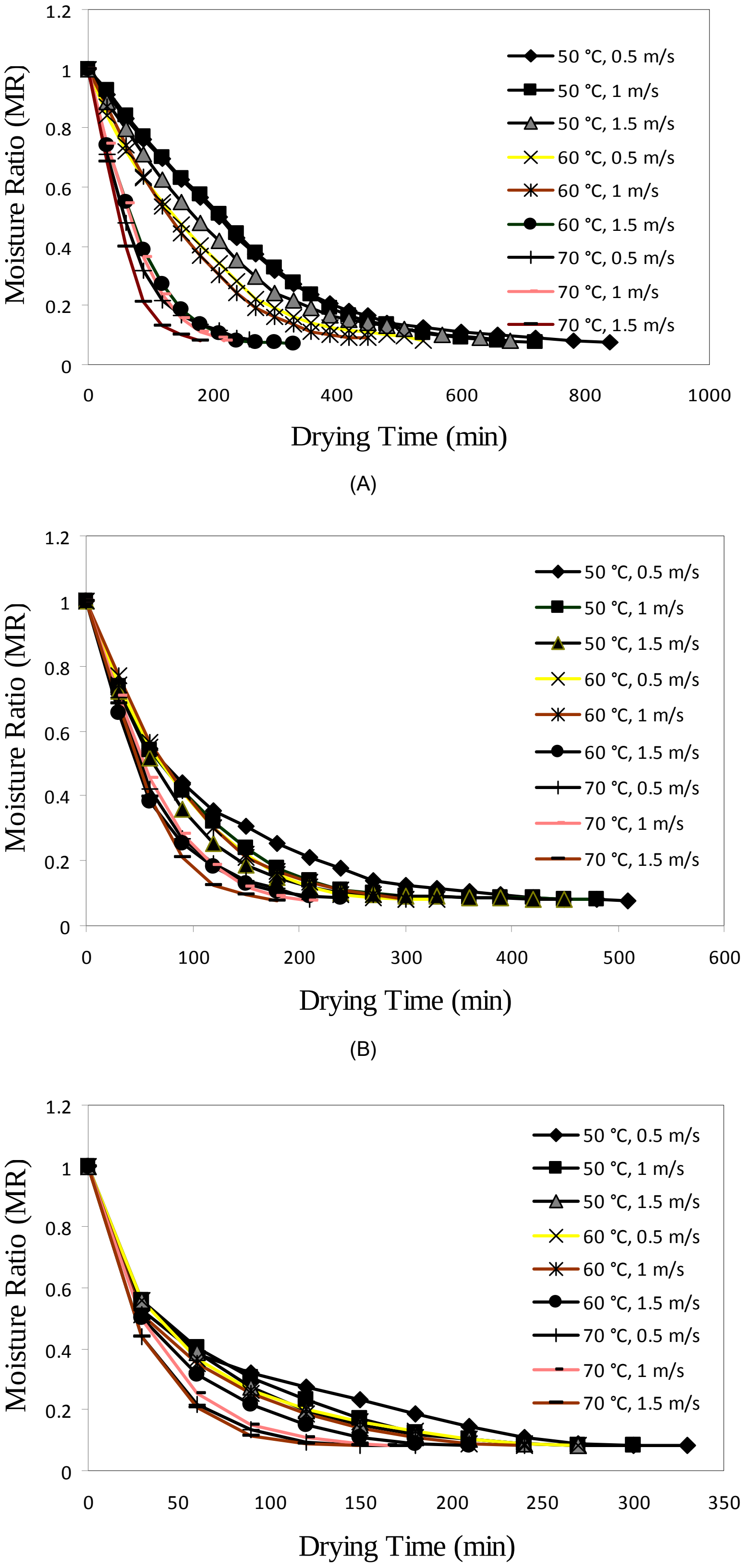
Figure 2 presents the variations of moisture ratio as a function of drying time at temperatures of 50, 60 and 70 °C. It was noticed from these figures that temperature and velocity of drying air affected on drying rates pomegranate samples.

Figure 3 demonstrates energy utilization trend during the drying of pomegranate arils in the control treatment. As shown in this figure, energy utilization decreases with time, its maximum value occurring at the inception of drying process. The reason is that moisture transfer by air was higher in the beginning of drying than at latter stages. These observations for energy utilization resembles those made for convection drying of apple slices [3], silicon drying of potato and pumpkin slices [7-8], energy and exergy analyses of thin-layer drying of coroba slices [4] and carrot cubes [13].

Increasing temperature and inlet air flow raised the energy utilization and inlet air enthalpy. Enthalpy increase, in turn, increased mass and heat transfer which translates into higher energy utilization. The maximum value of energy utilization in the drying of control samples obtained was 0.269 kJ/s at air temperature of 70 °C and velocity of 1.5 m/s. Furthermore, the minimum value obtained was 0.102 kJ/s at a temperature of 50 °C and velocity of 0.5 m/s.

Figure 4 illustrates energy utilization during the drying of pomegranate arils using the 100 W microwave pretreatment. As shown, energy utilization decreased in comparison with control treatment. This is because a considerable amount of moisture would be removed as free water drying pretreatment. Meanwhile, energy utilization increased with temperature and air velocity, which is similar to the trend occurring in the control treatment. The maximum value of energy utilization was found to be 0.269 kJ/s using the 100 W microwave pretreatment at temperature of 70 °C and air velocity of 1.5 m/s. Conversely, the minimum value was found to be 0.051 kJ/s at the temperature of 50 °C and air velocity of 0.5 m/s.

Figure 5 depicts energy utilization for drying of pomegranate arils using 200 W microwave pretreatment. It is observed that in comparison with the 100 W pretreatment, energy utilization decreased using this



(A)

(B)

Figure 2. Variation of moisture ratio as a function of drying time at A) control treatment, B) 100 W microwave pretreatment and C) 100 W microwave pretreatment.

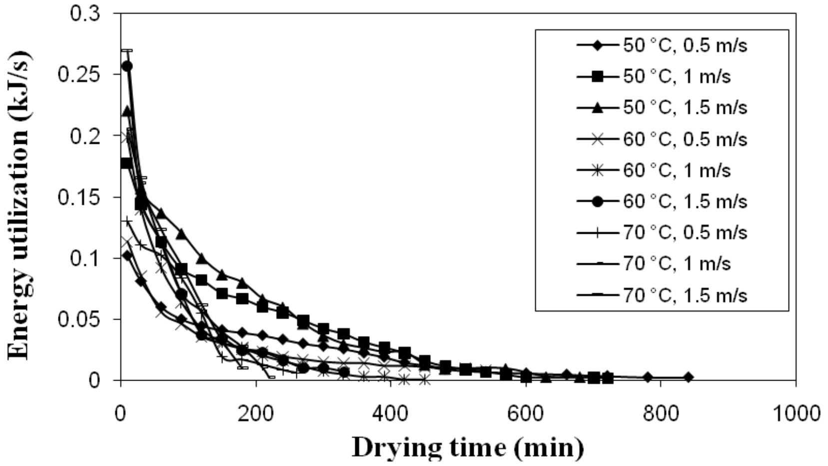


Figure 3. Effect of air temperature and velocity on energy utilization (control treatment).

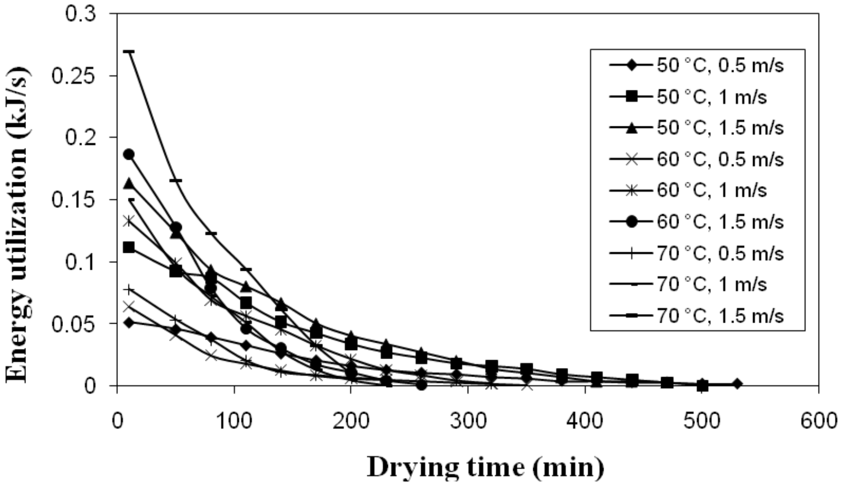


Figure 4. Effect of air temperature and velocity on energy utilization (100 W pretreatment).

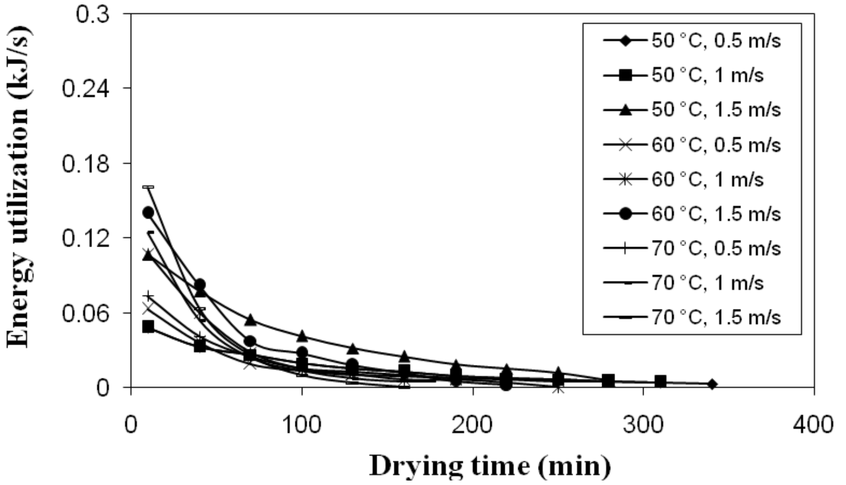


Figure 5. Effect of air temperature and velocity on energy utilization (200 W pretreatment).

pretreatment, since much moisture was removed at the microwave medium. Moreover, increase in air temperature and air velocity leads to higher energy utilization. The amount of energy consumption for drying of pomegranate arils is obtained from Eq. (1). The difference between inlet and outlet air enthalpy determines the energy consumption for drying of arils. Since the initial temperature of product by using the 200 W pretreatment was higher than the other pretreatments, therefore, considering the higher initial temperature of the samples, the inlet and outlet enthalpy were lower than for the other two treatments and consequently the energy consumption was reduced. The maximum energy utilization was calculated to be 0.161 kJ/s at 70 °C and air velocity of 1.5 m/s. The temperature of 50 °C and air velocity of 0.5 m/s yielded the minimum value of energy utilization, which was 0.048 kJ/s.

Comparing the energy levels of the 3 treatments proved that energy utilization and drying time decreased significantly using 10-min microwave pretreatment with 200 W. Energy utilization depends on air velocity, latent heat of water vapor, specific heat of air and outlet air temperature. Values of these factors, excluding outlet air temperature, are close to each other for the three treatments. However, since the warming action in the 200 W microwave treatment is more pronounced compared to the 100 W treatment, higher sample temperature at the onset of convection drying is expected. Subsequently, outlet temperature of the dryer would be higher and of course closer to the inlet temperature. As a result, energy utilization would be low.

Energy utilization ratio

Energy utilization ratio (EUR) against drying time at constant temperature for various air velocities is presented in Figure 6. It is seen that EUR decreased with time. Based on Eq. (7), the decrease in energy utilization ratio is reasonable, since energy utilization decreases with time. The maximum value of energy utilization ratio was obtained to be 0.004 for drying at temperature of 50 °C and air velocity of 1.5 m/s. The minimum value of 0.001 was obtained at 70 °C with air velocity of 0.5 m/s. These results resemble those reported by Akpinar [6] for drying pumpkin slices in silicon dryer and Nazghelichi [13] for drying carrot cubes.

Figure 7 shows the trend of energy utilization ratio using the 100 W microwave pretreatment. The decreasing trend of energy utilization ratio is observed. At the control treatment, energy utilization ratio decreases more dramatically. This is because energy utilization is lower with the 100 W microwave pretreatment. The temperature of 50 °C and air velocity of 1.5 m/s resulted in the maximum value of 0.005 for energy utilization ratio. The minimum value of 0.001 was obtained for EUR using 70 °C and air velocity of 0.5 m/s.

Figure 8 illustrates variation of energy utilization ratio against drying time using 200 W microwave pretreatment. Since energy utilization is lower compared to the 100 W pretreatment (Figure 7), EUR is lower as well. The maximum value of energy utilization ratio using the 200 W microwave pretreatment was obtained to be 0.002835 at the temperature of 50 °C and air velocity of 1.5 m/s, while the minimum value was 0.000662 obtained at 70 °C and 0.5 m/s combination. These results are quite similar to the energy utilization values obtained in the control treatment.

Comparing the energy utilization ratios for the three experimental treatments indicates that energy utilization ratio was maximum in the control treatment and minimum in the 200 W microwave treatment.

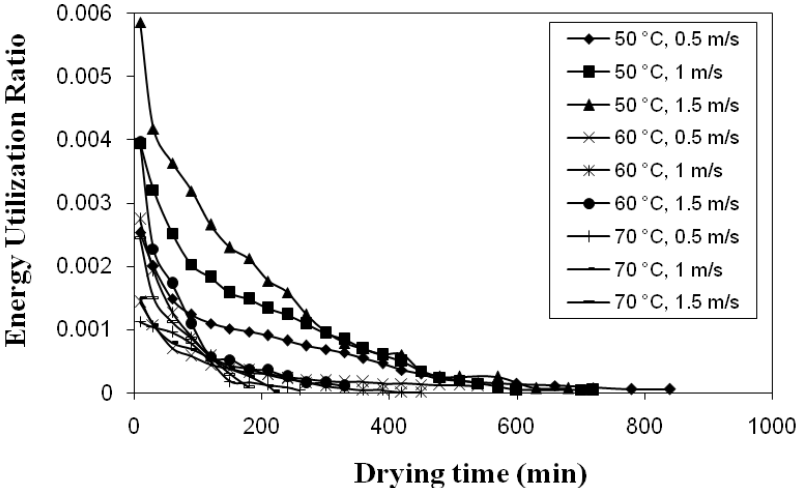


Figure 6. Effect of air temperature and velocity on energy utilization ratio (control treatment).

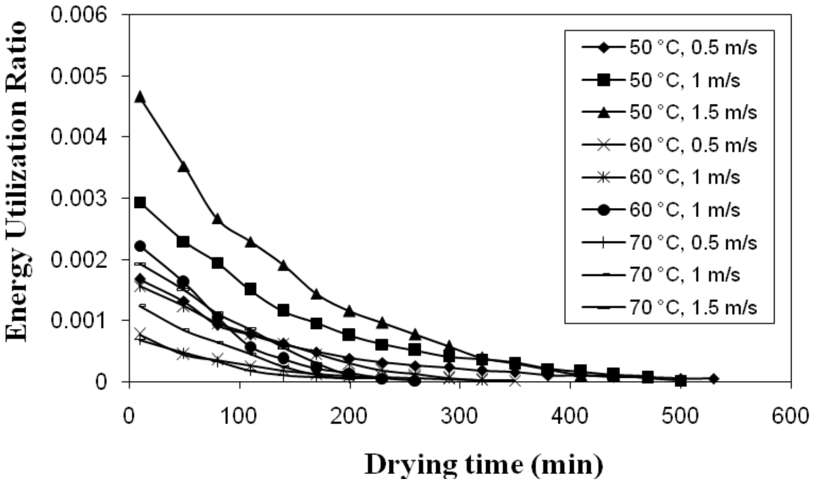


Figure 7. Effect of air temperature and velocity on energy utilization ratio (100 W pretreatment).

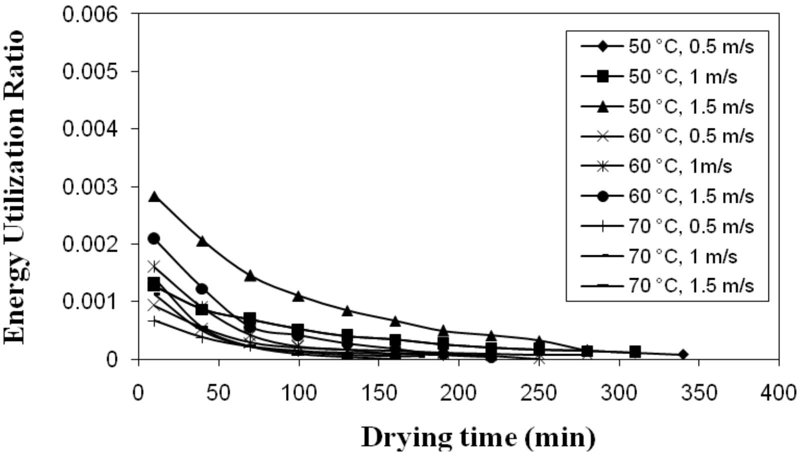


Figure 8. Effect of air temperature and velocity on energy utilization ratio (200 W pretreatment).

This is because energy utilization ratio is calculated by dividing the utilized energy to the energy provided for drying. The denominator of EUR is constant for all the treatments while the energy utilization varies. As mentioned, energy utilization would have its minimum value using the 200 W microwave pretreatment. Accordingly, energy utilization ratio would also be minimum at this treatment.

Exergy

Table 1 depicts the outlet exergy of pomegranate arils in the control, for 100 and 200 W microwave treatment. The table shows that a negligible part of the provided energy in the dryer is wasted, thus energy is available at the outlet. This indicates that exergy loss is high at large values of air temperature and velocity. The maximum exergy loss for drying of control samples was 0.157 kJ/s observed at the temperature of 70 °C and air velocity of 1.5 m/s while the minimum value was found to be 0.044 kJ/s at 50 °C and 0.5 m/s. These observations were similar to the results obtained for drying red pepper [3], cyclone-type drying of potato slices [8], drying pumpkin slices [10], solar drying of pistachio [9] and carrot cubes [13]. Moreover, the exergy loss in the control treatment is higher than the exergy loss using the 100 W microwave treatment. Maximum exergy loss was found to be 0.109 kJ/s at the temperature of 70 °C and air velocity of 1.5 m/s using the 100 W microwave treatment and the minimum value was calculated to be 0.034 kJ/s at 50 °C and 0.5 m/s. Exergy loss in 200 W treatment is lower than those in the control or 100 W treatments. Its maximum value was obtained to be 0.103 kJ/s at 70 °C and air velocity of 1.5 m/s. Here, the minimum value of 0.023 kJ/s was obtained using of 50 °C and air velocity of 0.5 m/s. These results are similar to the exergy loss for control treatment.

Comparison of exergy loss values in the three treatments shows that its maximum and minimum values are obtained using the control and the 200 W

Table 1. The results of exergy loss and exergy efficiency analysis

Parameters and conditions	Control treatment		Microwave treatment			
			100 W		200 W	
	Exergy loss, kJ/s	Exergy efficiency	Exergy loss kJ/s	Exergy efficiency	Exergy loss kJ/s	Exergy efficiency
T = 50 °C, V = 0.5 m/s	0-0.4390	44.85-100	0-0.0336	62.54-100	0-0.0235	73.68-100
T = 50 °C, V = 1 m/s	0- 0.0828	53.75-100	0-0.0634	64.58-100	0-0.0395	78.45-100
T = 50 °C, V = 1.5 m/s	0-0.1037	60.19-100	0-0.0798	70.47-100	0-0.0626	79-71-100
T = 60 °C, V = 0.5 m/s	0-0.0610	60-79-100	0-0.0410	71.25-100	0-0.0349	77.05-100
T = 60 °C, V = 1 m/s	0-0.1164	64.05-100	0-0.0669	77.74-100	0-0.0656	79.66-100
T = 60 °C, V = 1.5 m/s	0-0.1493	66.21-100	0-0.0875	82.34-100	0-0.0840	82.23-100
T = 70 °C, V = 0.5 m/s	0-0.0930	76.20-100	0-0.0519	76.67-100	0-0.0406	80.11-100
T = 70 °C, V = 1 m/s	0-0.1399	77.07-100	0-0.0856	80.93-100	0-0.0783	82.26-100
T = 70 °C, V = 1.5 m/s	0-0.1573	77.68-100	0-0.1090	84.75-100	0-0.1026	83.36-100

microwave treatments, respectively. Exergy loss is basically calculated by subtracting outlet exergy from inlet exergy. Moreover, exergy loss is a function of inlet and outlet air flow and medium temperature. At three treatments, all the parameters except the outlet air temperature are close to each other (as stated for calculation of energy utilization). Outlet temperature increased in the 200 W microwave treatment, resulting in a small difference between outlet and inlet exergy value. Therefore, exergy loss would be low using the 200 W microwave pretreatment.

Exergy efficiency

Table 1 refers to outlet exergy as the main factor of low thermodynamic efficiency of dryers. They also indicate that a major part of provided exergy is wasted as outlet air exergy. Another reason of low exergy efficiency is heat losses from the dryer body. The maximum exergy efficiency for control treatment was calculated to be 0.776 at the temperature of 70 °C and air velocity of 1.5 m/s. The minimum value resulted using air temperature and velocity of 50 °C and 0.5 m/s, respectively. These observations were similar to those obtained in carrot cubes drying [13], red pepper drying [3], cyclone type drying of potato slices [8], pumpkin slice drying [10], solar drying of pistachio [9] and energy and exergy analysis using of timber drying with assisted heat pump [11]. Exergy efficiency was lower for the control treatment compared to the 100 W microwave treatment. The reason is the higher initial temperature of samples placed in the dryer due to microwave pretreatment, resulting in increased outlet temperature. The maximum exergy efficiency for 100 W microwave treatment was 0.847 at the temperature of 70 °C and air velocity of 1.5 m/s. The minimum value of 0.625 was obtained using air temperature of 50 °C and air velocity of 0.5 m/s.

Effect of inlet air flow at constant temperature on exergy efficiency during thin-layer drying of 200 W microwave pretreated samples is shown in Table 1. Exergy efficiency is higher for control and 100 W treatments compared to the 200 W treatment. Air temperature of 70 °C and air velocity of 1.5 m/s are the conditions in which the maximum exergy efficiency of 0.834 occurs. The minimum value is obtained to be 0.737 at 50 °C and 0.5 m/s air temperature and velocity, respectively.

CONCLUSIONS

Energy and exergy analysis for drying of thin layer sour pomegranate arils were preformed in this study. Experiments were conducted at various air temperatures (50, 60 and 70 °C), air velocities (0.5, 1 and 1.5 m/s) and three pretreatments (control, 100 W microwave pretreatment for 20 min and 200 W microwave pretreatment for 10 min). The following conclusions may be made based on statistical analysis of the data:

1. Energy utilization decreased with drying time in all the treatments. Maximum value of energy utilization was obtained with the control treatment (hot air drying only) and the minimum for the 200 W microwave pretreatment.
2. Energy utilization ratio showed a decreasing trend with time all the treatments. Control samples used the maximum energy while 200 W microwave pretreated samples needed the minimum energy.
3. Exergy loss increased with time, i.e. all the input energy was removed from the system. The maximum and minimum exergy losses were observed for the control and 200 W microwave treatments, respectively.
4. Exergy efficiency increased with time, i.e. all the input energy was removed from the system at the

end of drying the process. The maximum and minimum exergy loss efficiency values were obtained using the control and the 200 W microwave treatments, respectively.

Results of energy and exergy analyses indicate that the system was not thermodynamically very efficient for control treatment. This can be regarded as a drawback for such convection thin layer dryers. However, using microwave pretreatment improved the thermodynamic efficiency of the process (for both 100 and 200 W treatments compared to the control).

Nomenclature

EU	Energy utilization (kJ/s)
m	Mass flow rate (kg/s)
C	Specific heat (kJ/kg °C)
EUR	Energy utilization ratio (dimensionless)
h	Specific enthalpy (kJ/kg)
h_{fg}	Latent heat of vaporization of water (kJ/kg)
P	Atmospheric pressure (kPa)
P_{vs}	Saturated pressure (kPa)
T	Temperature (° C)
w	Humidity ratio of air (kg water/kg da)
ϕ	Relative humidity, %

Subscripts

∞	Surrounding or ambient
a	Air
d	Dry
i	Inlet
l	Loss
o	Outlet

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NAUČNI RAD

UTICAJ MIROTALASNOG PREDTRETMANA SEMENKI KISELOG NARA NA ISKORIŠĆENOST ENERGIJE I EKSERGIJE PRI SUŠENJU U TANKOM SLOJU

Energetska i eksergijska analiza se može smatrati važnim oruđem za projektovanje, analizu i optimizaciju toplotnih sistema. U radu se saopšteni rezulati energetske i eksergijske analize sušenja semenki kiselog nara u tankom sloju posle mikrotalasnog predtretmana. Korišćena su dva mikrotalasna predtretmana (100 W za 20 min i 20 W za 10 min), kao i kontrolni tretman (konvektivno sušenje bez mikrotalasnog predtretmana). Eksperimenti su sprovedeni na tri temperature vazduha (50, 60 i 70 °C) i pri tri brzine strujanja vazduha (0,5, 1,0 i 1,5 m/s). Rezultati su pokazali da se odnos iskorišćenosti energije i eksergije povćava sa vremenom, dok se eksergijska efkasnost smanjuje. Iskorišćenost energije i vreme sušenja se smanjuju značajno sa mikrotalsnim predtretmanom semenki nara. Minimalne vrednosti gubitaka i efikasnosti eksergije su utvrđene pri mikrotaslnom pretretmanu snage 200 W, dok su maksimalne vrednosti zapažene kod kontrolnog tretmana.

Ključne reči: energija i eksergija, mikrotalasni predtretman, sušenje u tankom sloju, nar.